Understanding the multi-phase structure and physical conditions of the ISM in nearby galaxies

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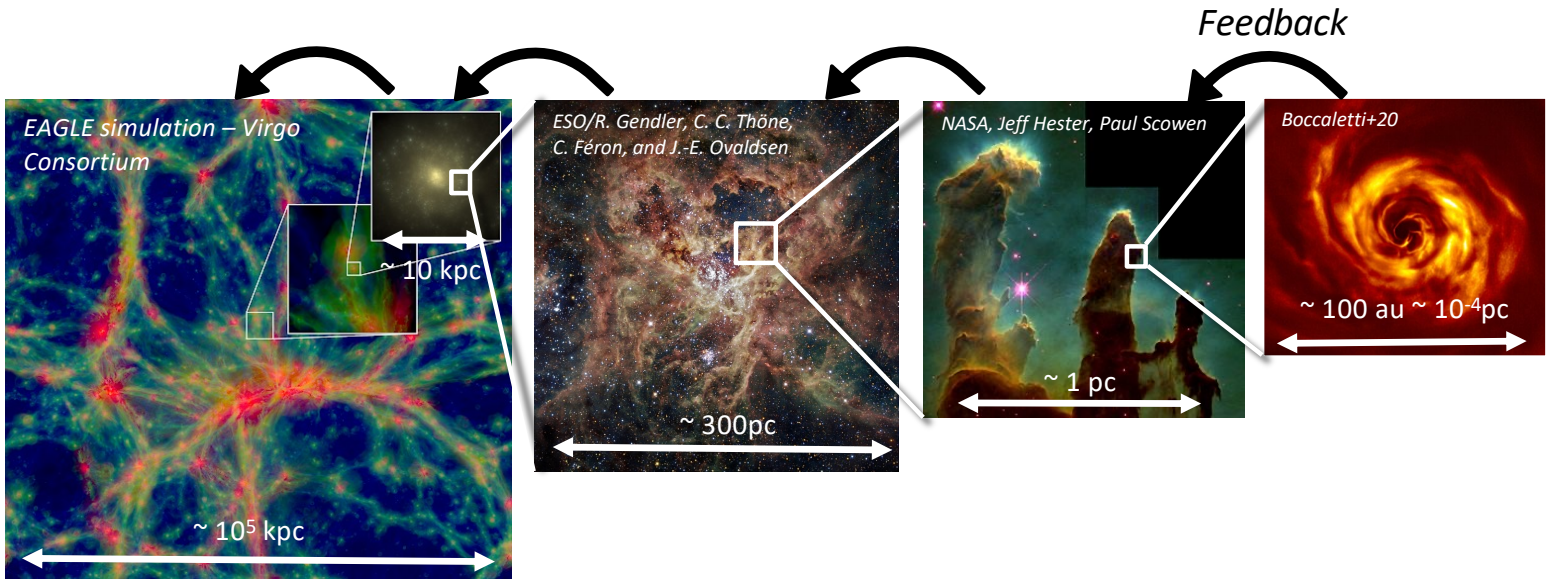
Lise Ramambason
Suzanne Madden
et al.

Heritage of SOFIA – Scientific Highlights and Future Perspectives — April 25th 2024

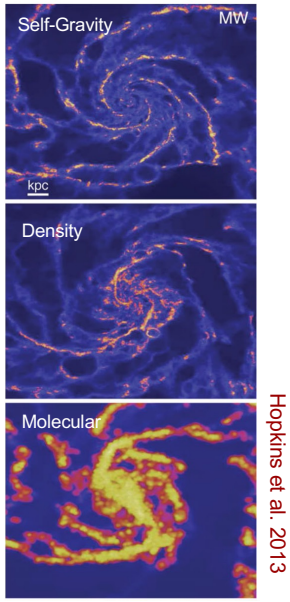
Star formation happens in a cosmological context



Uncertainties on the physics of star formation and feedback

Identical initial conditions, …

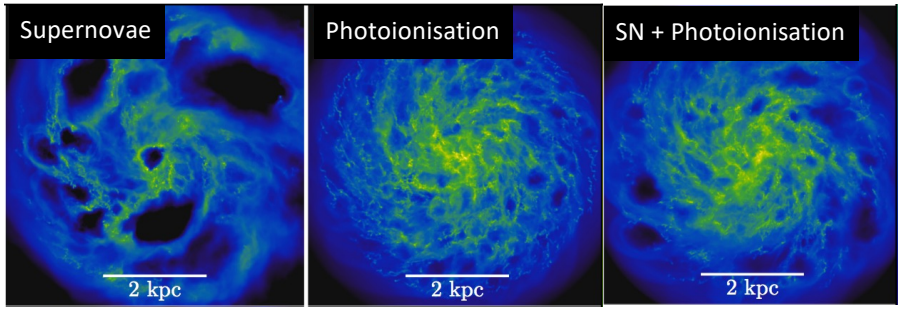
… different criteria for star-forming gas



Hopkins et al. 2013

Gas surface density:
blue – red – yellow

… different feedback prescriptions



Gas density: low – medium – high

Smith et al. 2021

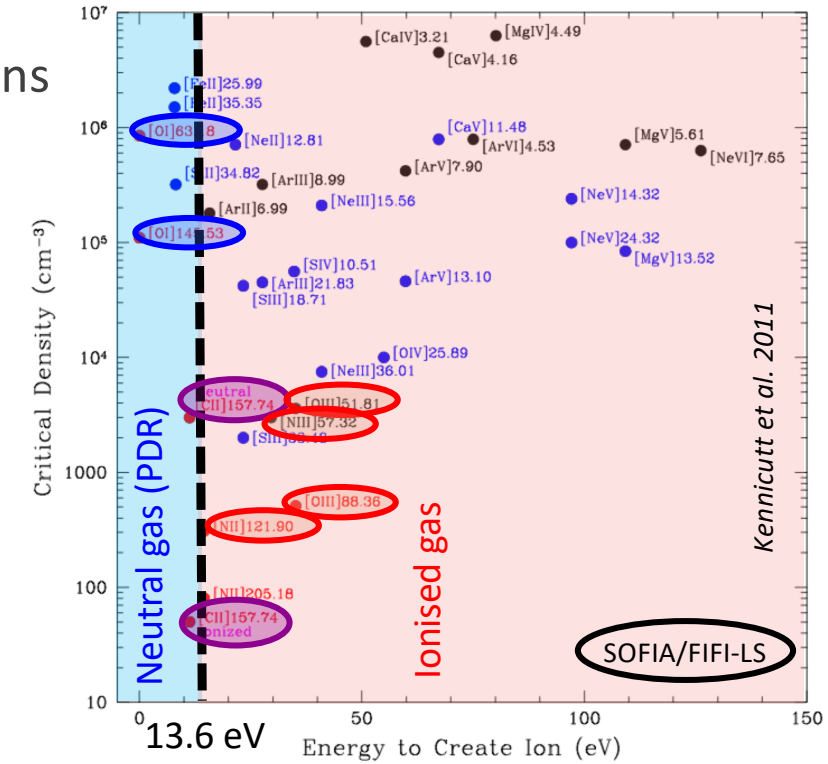
Uncertainties on the physics of star formation and feedback

- What are the effects of feedback on the surrounding medium?
  - What are the characteristics of the radiation field?
  - What are the physical conditions of the multi-phase ISM?
  - Are the molecular clouds destroyed by feedback?
- What is the (total) reservoir of star-forming gas?

Mélanie Chevance

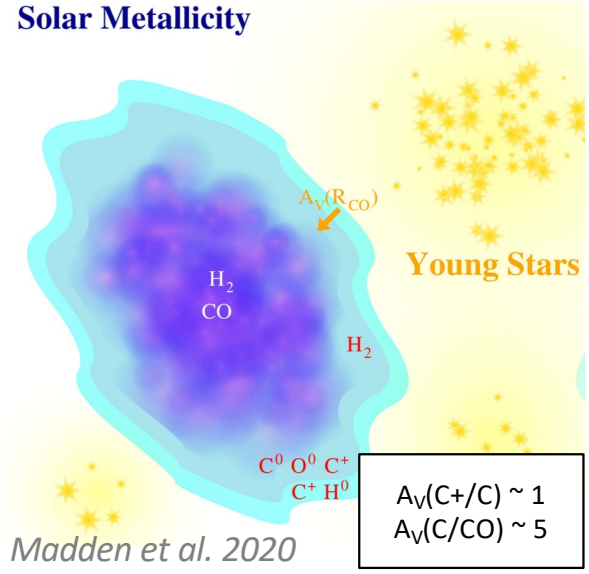
Uncertainties on the physics of star formation and feedback

1) **Multi-wavelength** observations



Uncertainties on the physics of star formation and feedback

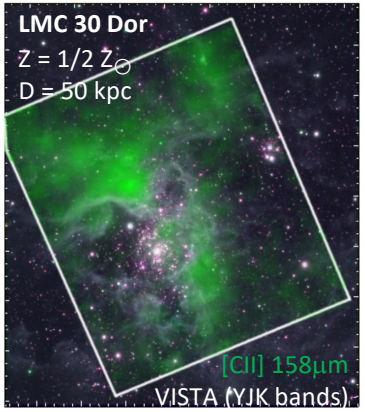
1) **Multi-wavelength** observations
2) In a **variety of environments**

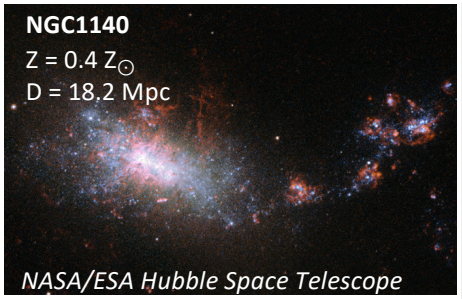


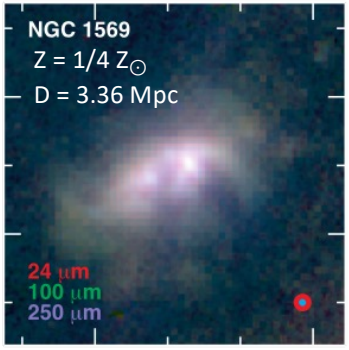
Madden et al. 2020

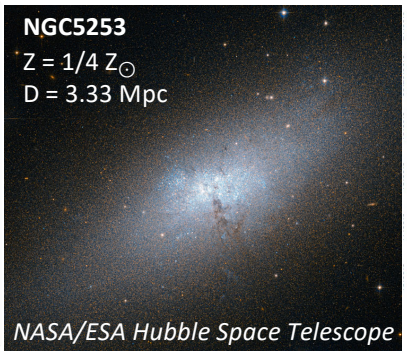
Uncertainties on the physics of star formation and feedback

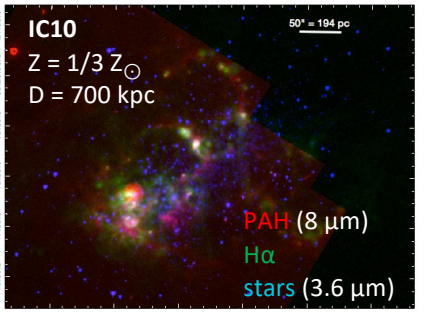
1) **Multi-wavelength** observations
2) In a **variety of environments**
3) At **high spatial resolution**





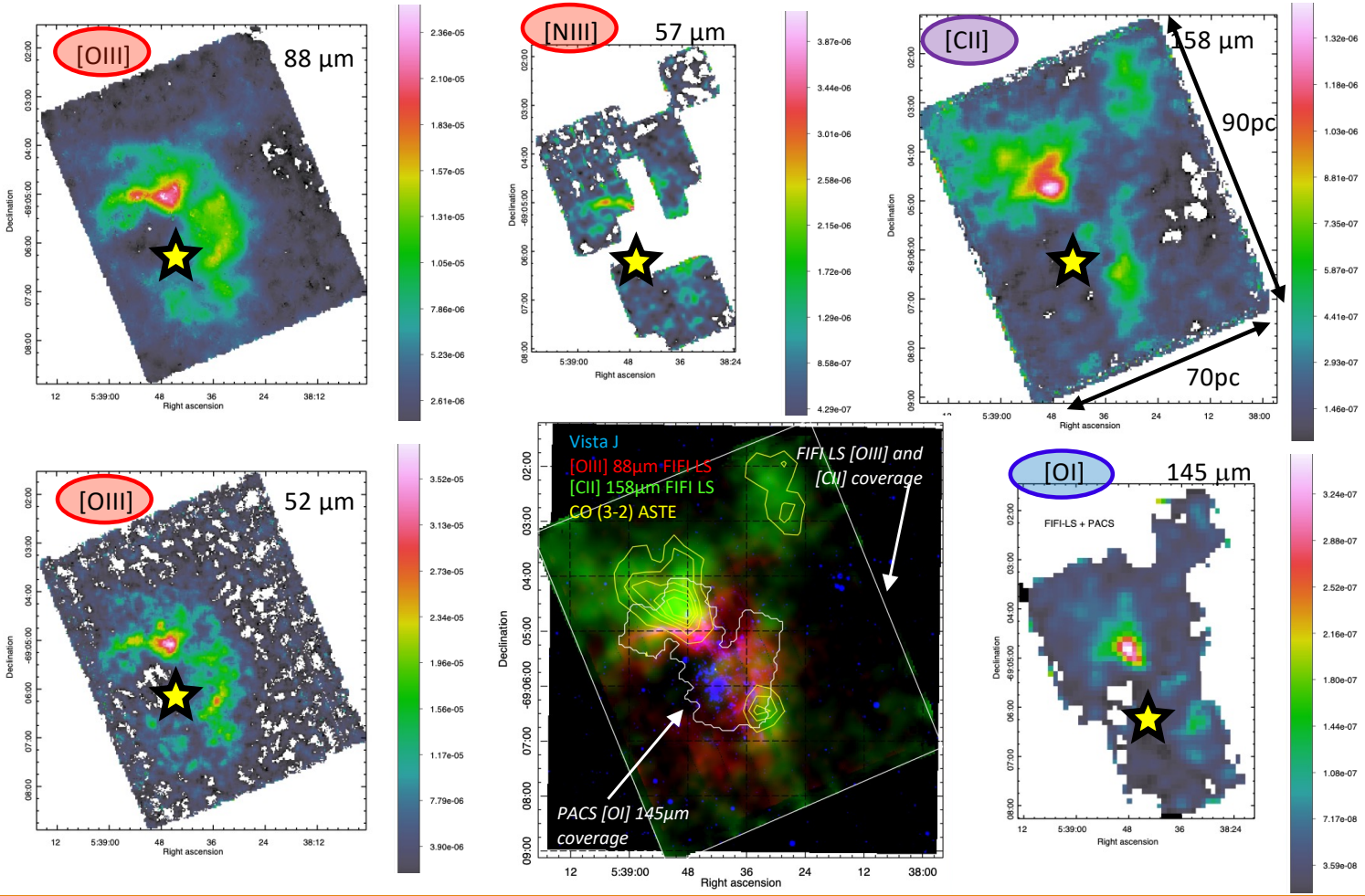






30Dor: SOFIA/FIFI-LS data

$Z = 1/2\ Z_{\odot}$



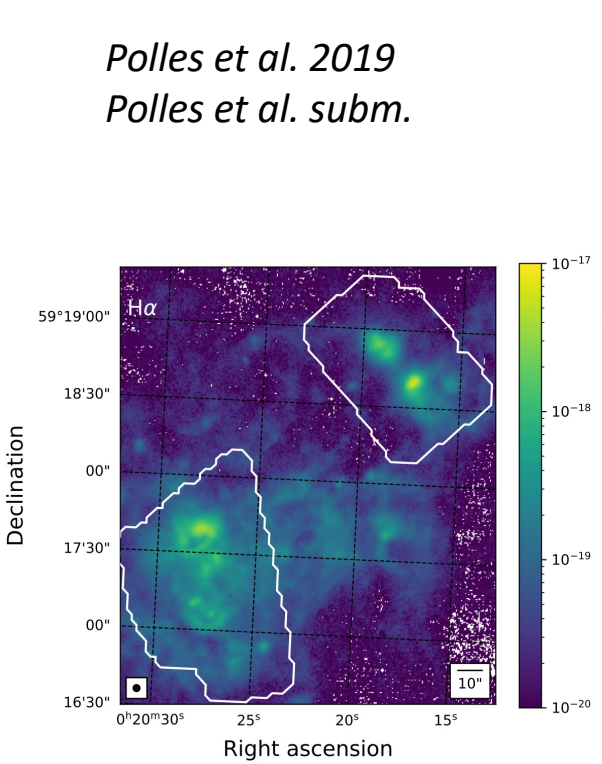
Chevance et al. 2020b

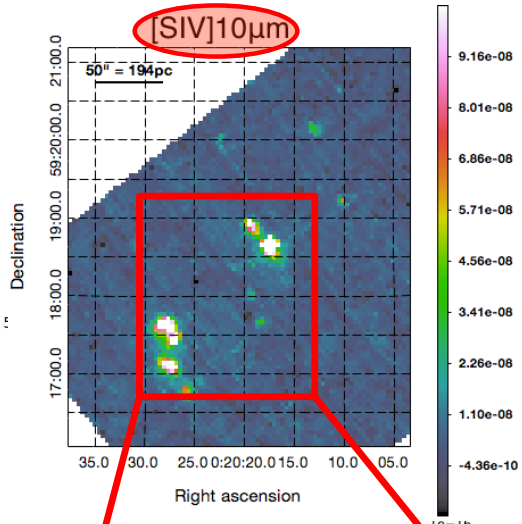
→ Also see Cornelia Pabst's talk

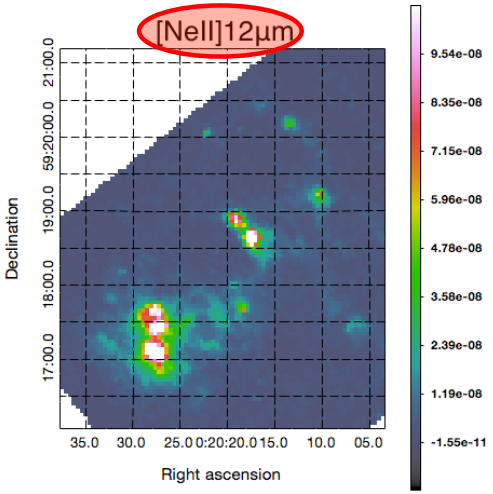
IC10: *Spitzer, Herschel & SOFIA* data

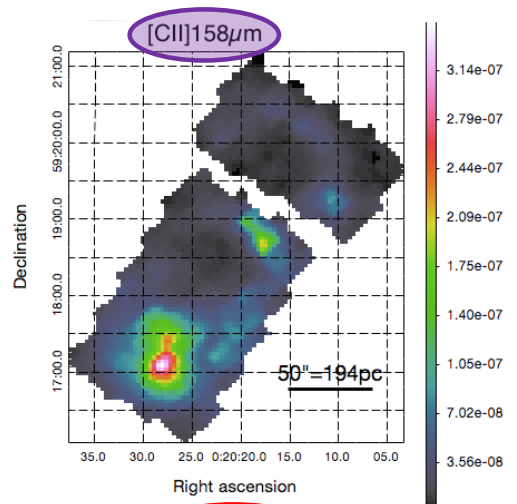
$Z = 1/3\ Z_{\odot}$

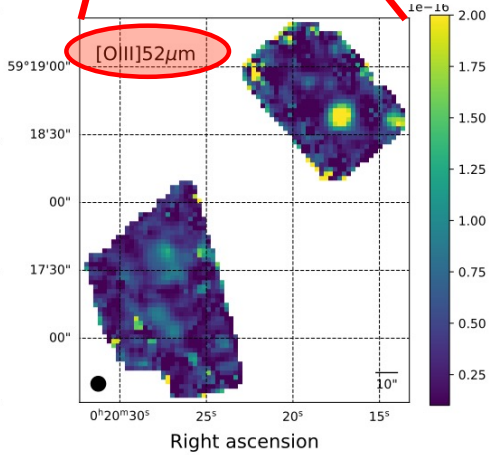
Polles et al. 2019
Polles et al. subm.

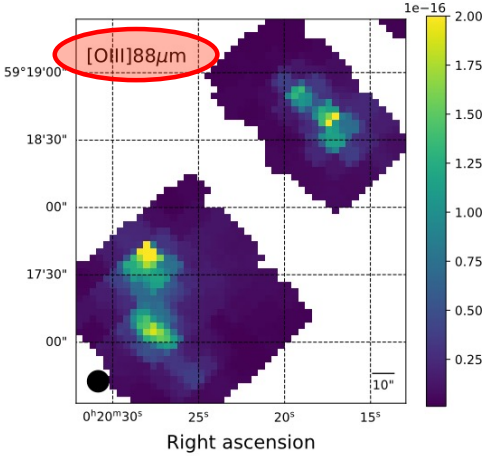


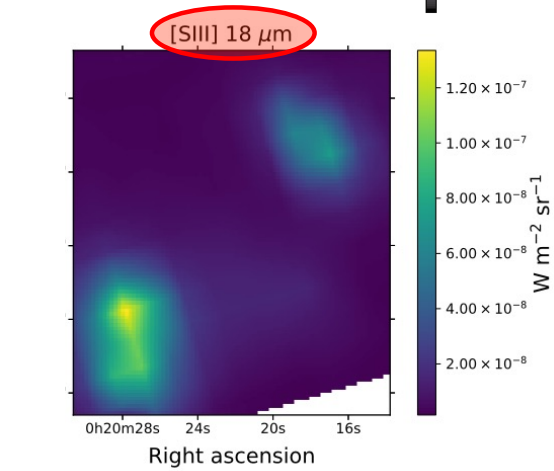




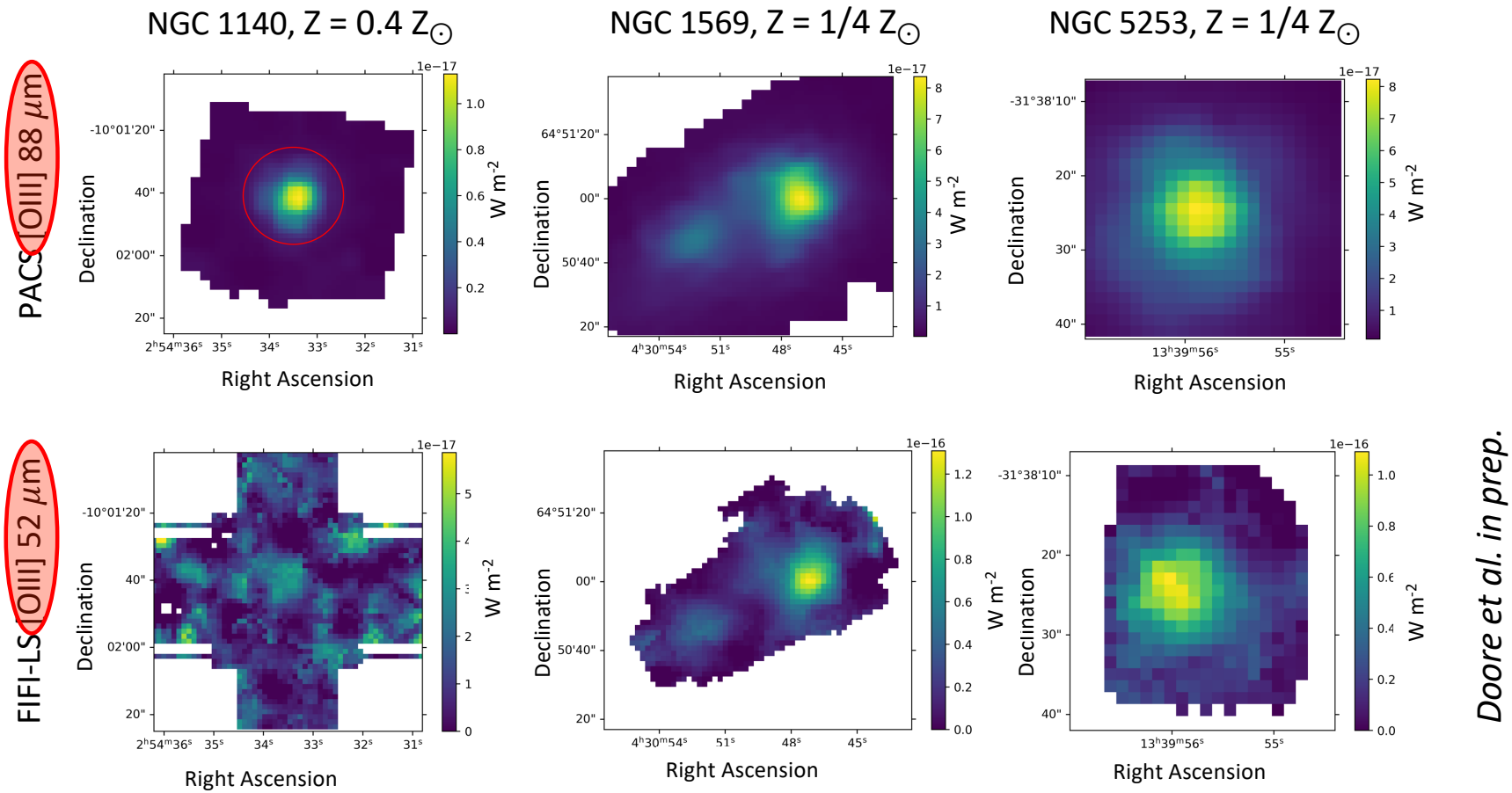






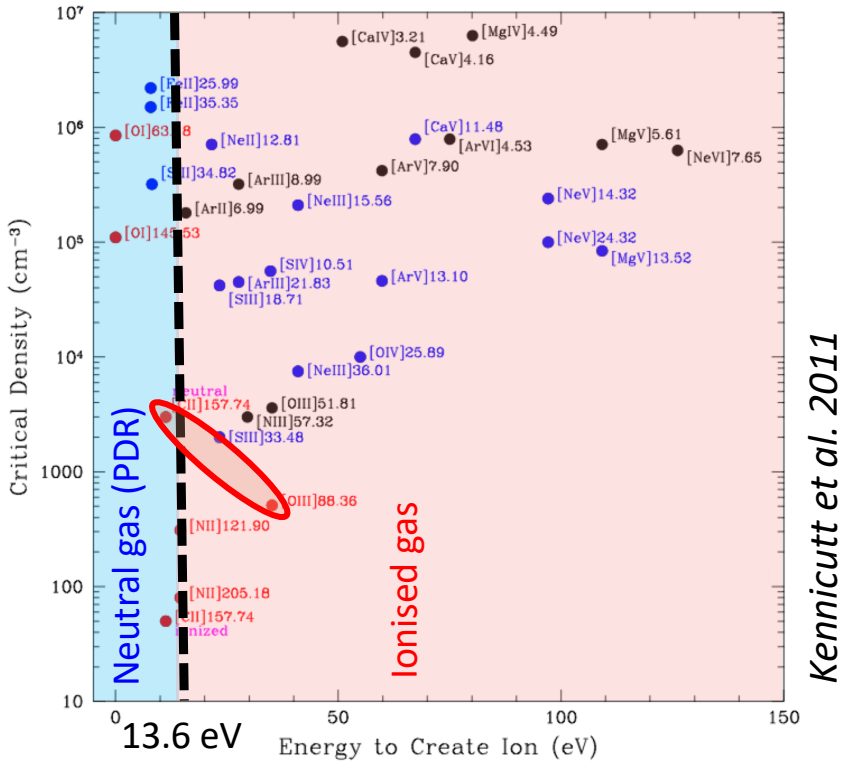


Nearby low-Z galaxies: *Herschel* and *SOFIA/FIFI-LS*



Doore et al. in prep.

Effect of feedback on large scales:
Hardness of the radiation field



Kennicutt et al. 2011

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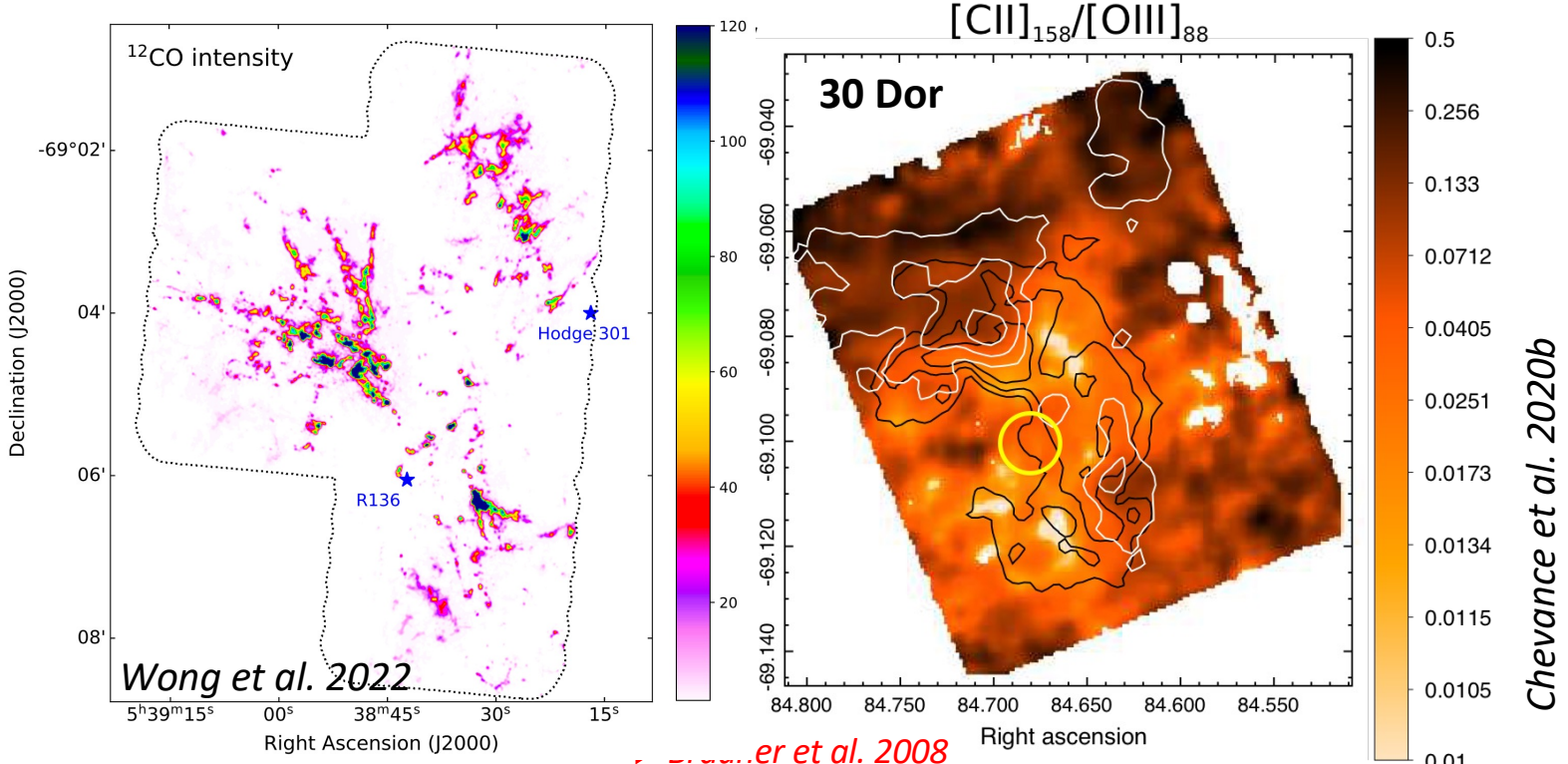


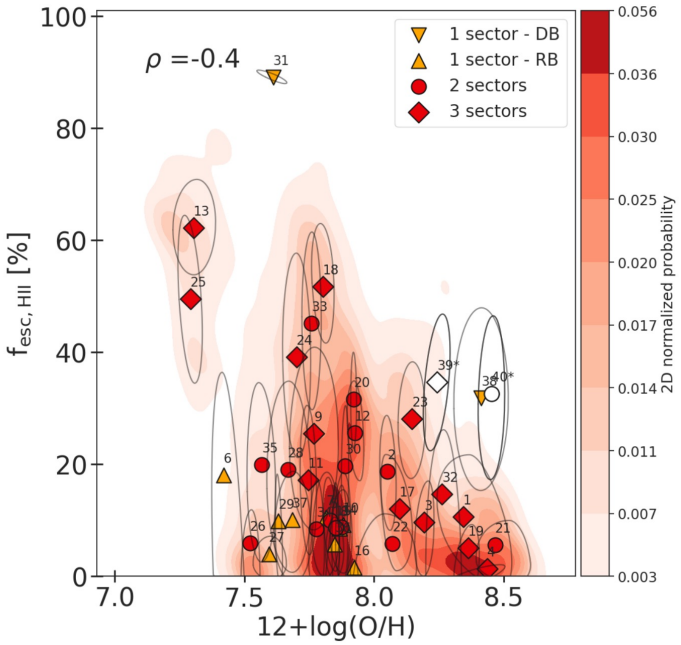
➢ More porous ISM at lower metallicities

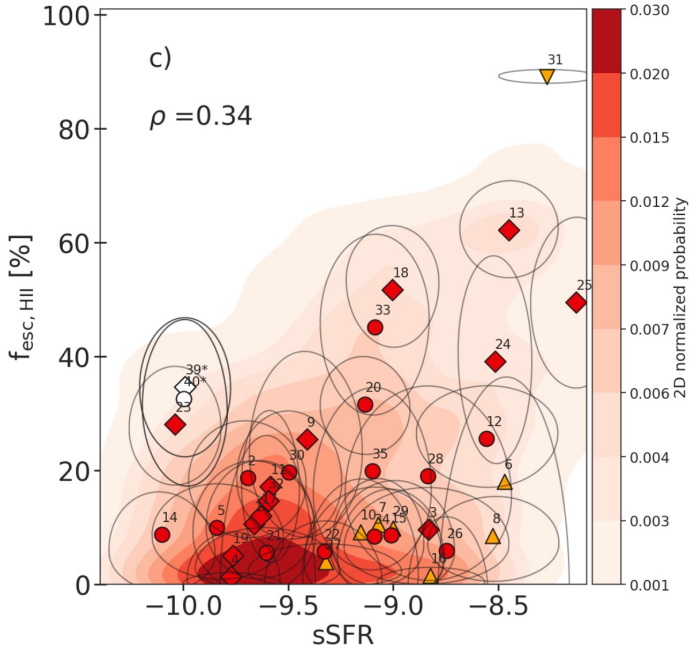
~ solar metallicity galaxies

Effect of feedback on large scales:
Porosity of the ISM

- More porous ISM at lower metallicities —> higher HII region escape fractions
- Higher escape fractions at high sSFR —> feedback dominated process

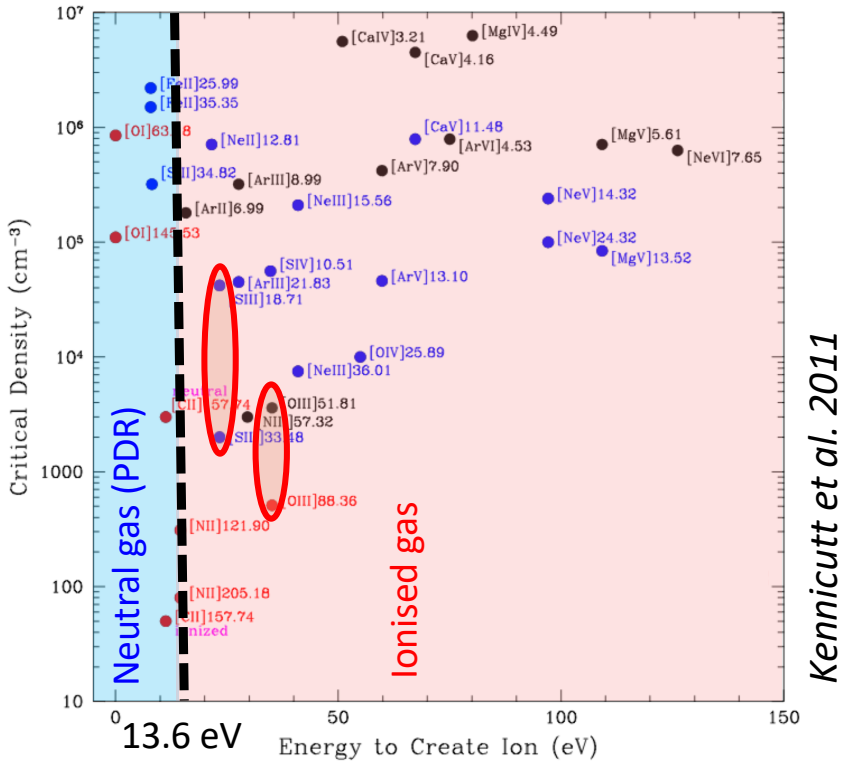
Dwarf Galaxy Survey





Ramambason et al. 2022

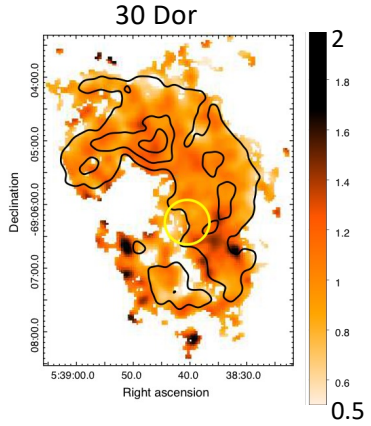
Effect of feedback on large scales:
Electron density in the ionised gas

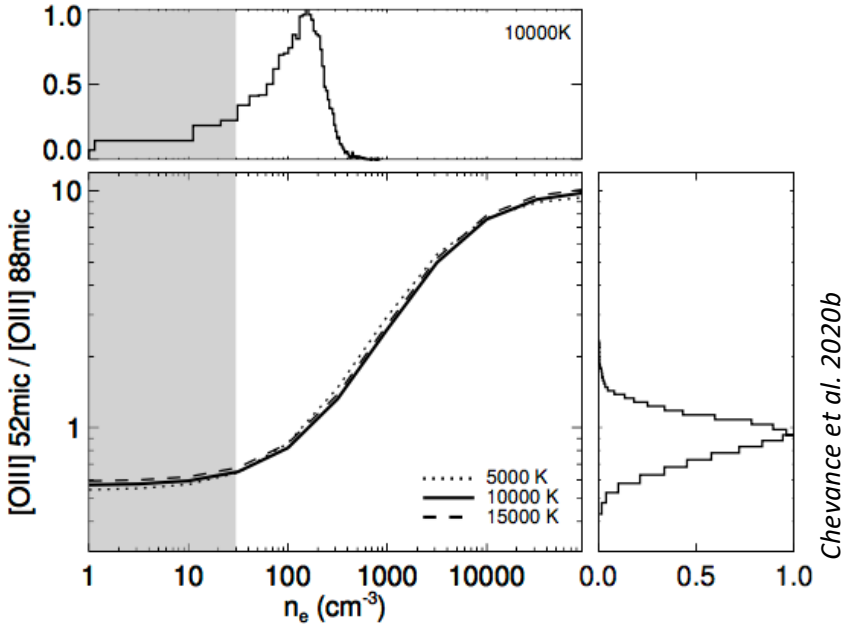


Kennicutt et al. 2011

Effect of feedback on large scales:
Electron density in the ionised gas

[OIII] 52μm / [OIII] 88μm





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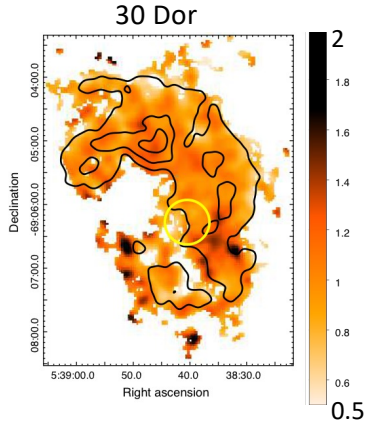
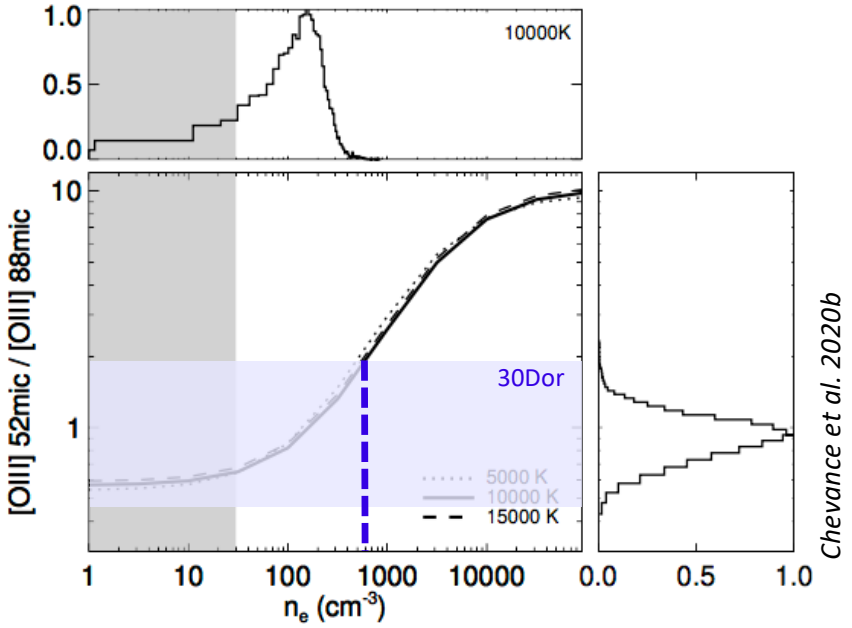
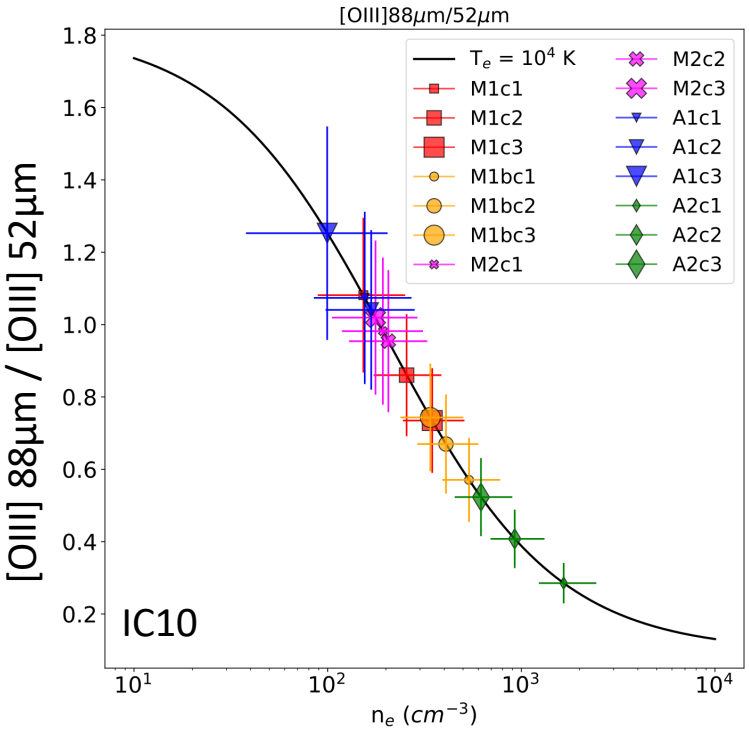
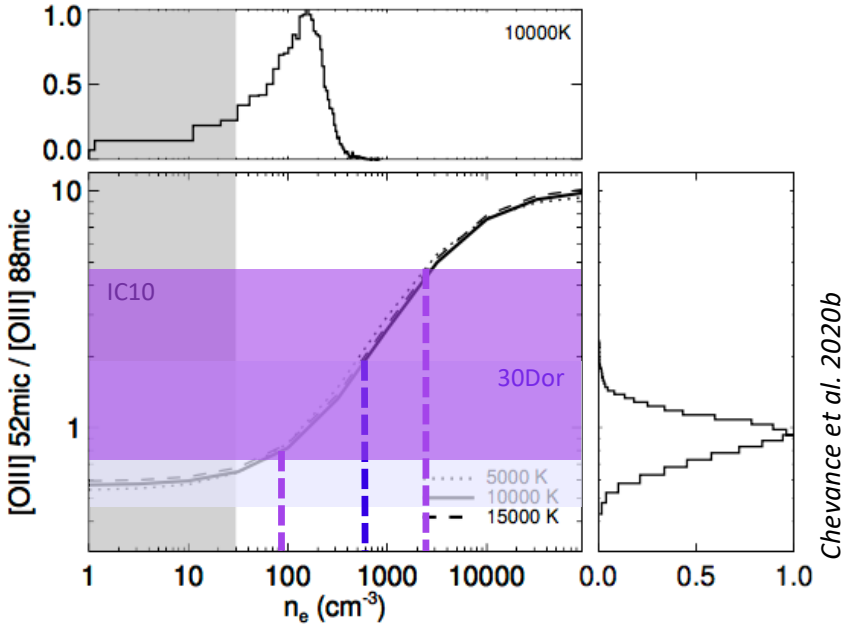




➢ 30Dor: electron density in the ionised gas < 600 cm^{-3}

Effect of feedback on large scales:
Electron density in the ionised gas





➢ 30Dor: electron density in the ionised gas < 600 cm^{-3}

➢ IC10: electron density 90 - 2440 cm^{-3}

Effect of feedback on large scales:
Electron density in the ionised gas

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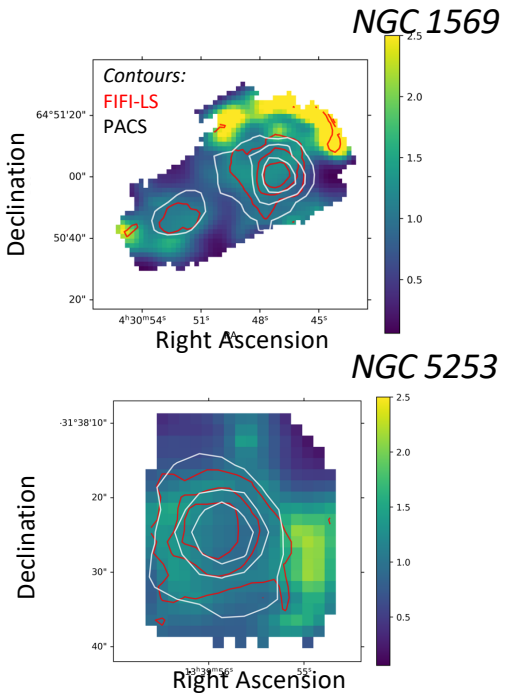

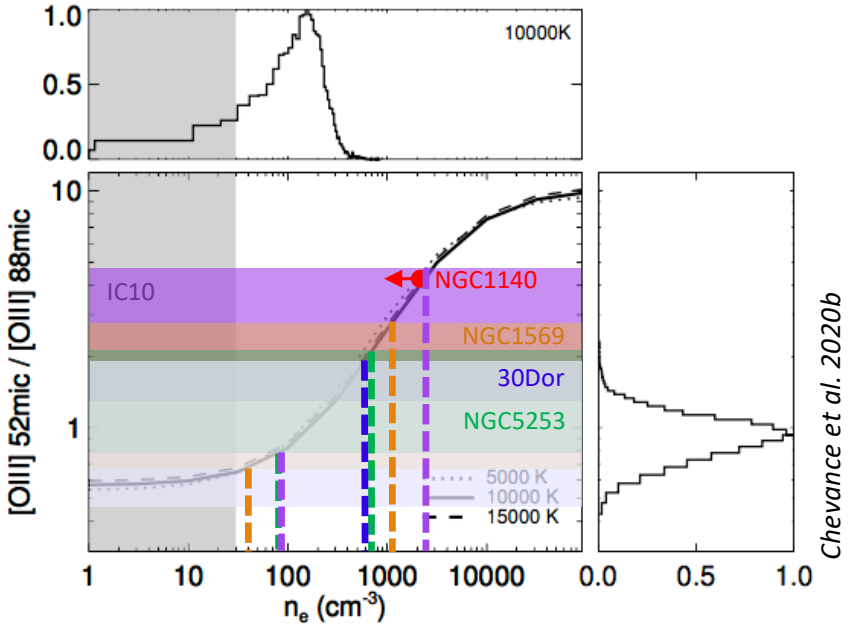

➢ 30Dor: electron density in the ionised gas < 600 cm^{-3}

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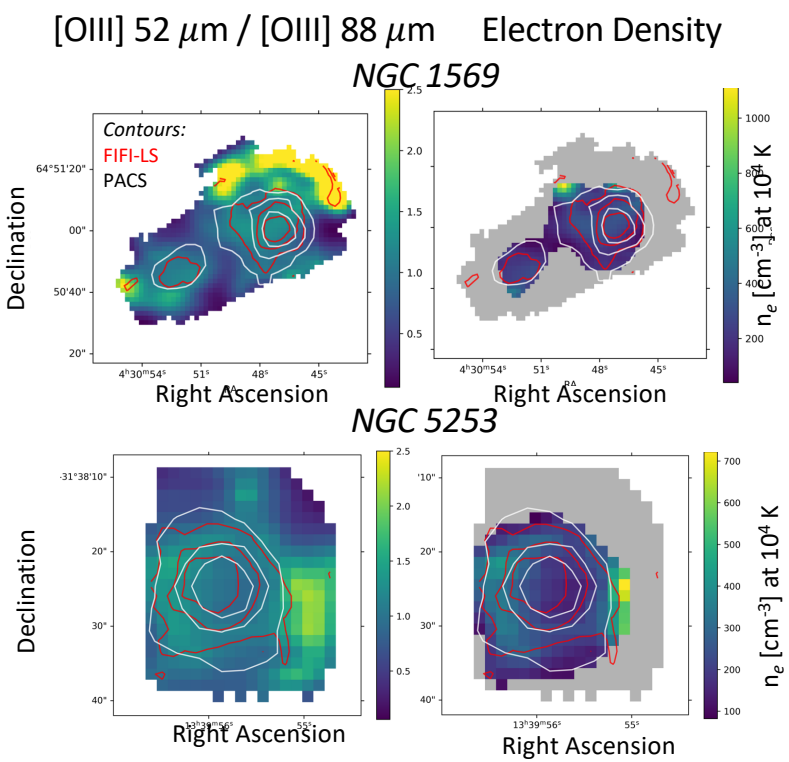
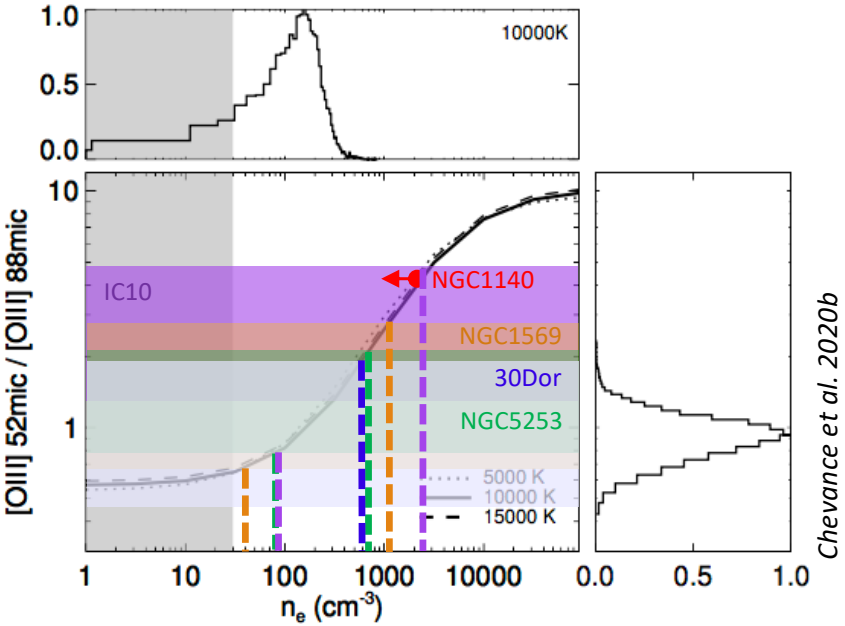
Effect of feedback on large scales:
Electron density in the ionised gas

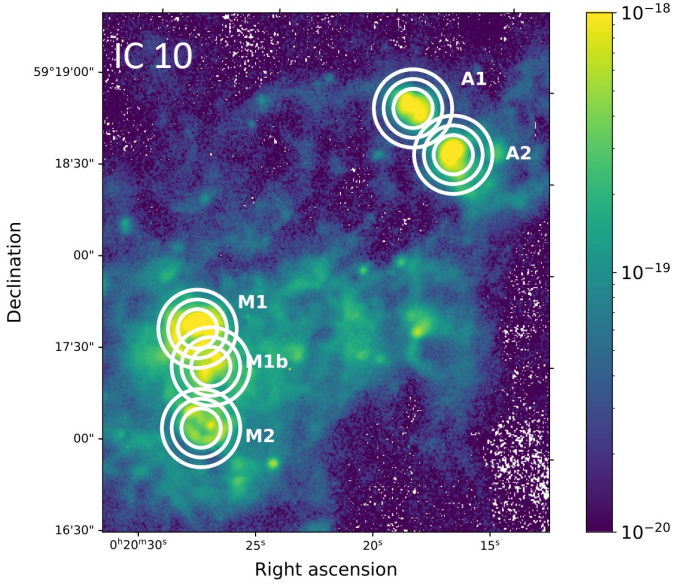


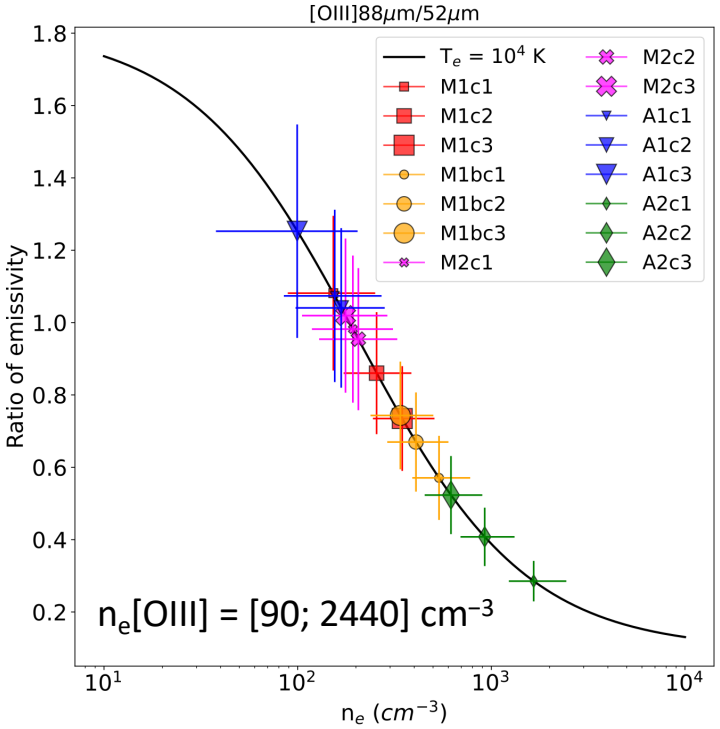


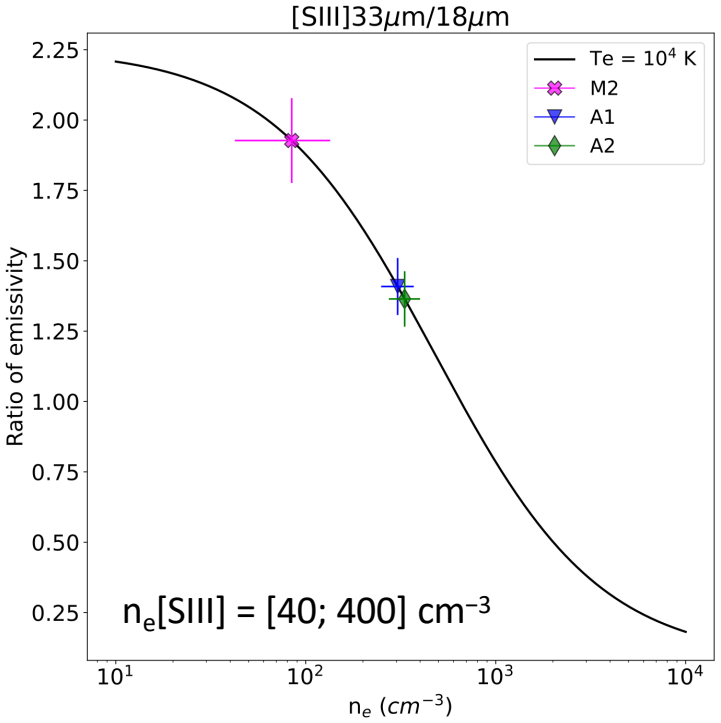
- 30Dor: electron density in the ionised gas < 600 cm^{-3}
- NGC1140: upper limit of 2330 cm^{-3}
- NGC1569: electron density 40 - 1100 cm^{-3}
- NGC5253: electron density 80 - 720 cm^{-3}
- IC10: electron density 90 - 2440 cm^{-3}

Effect of feedback on large scales:
Electron density in the ionised gas

Polles et al. subm.







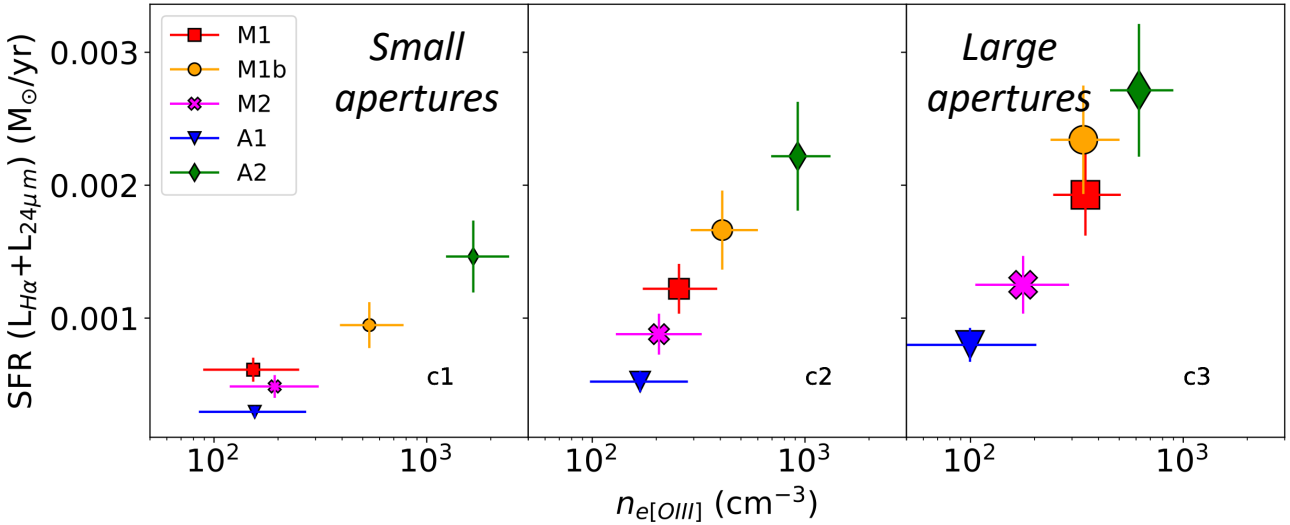
→ [OIII] and [SIII] trace ***two different components*** of the ionised gas.

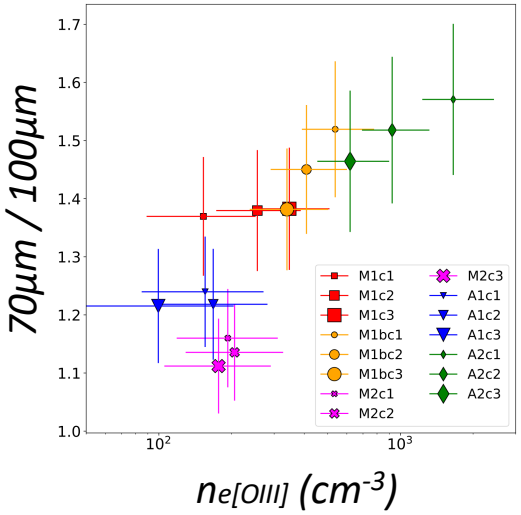
Effect of feedback on large scales:
Electron density in the ionised gas

IC10

Correlation with SFR and dust temperature

Polles et al. subm.





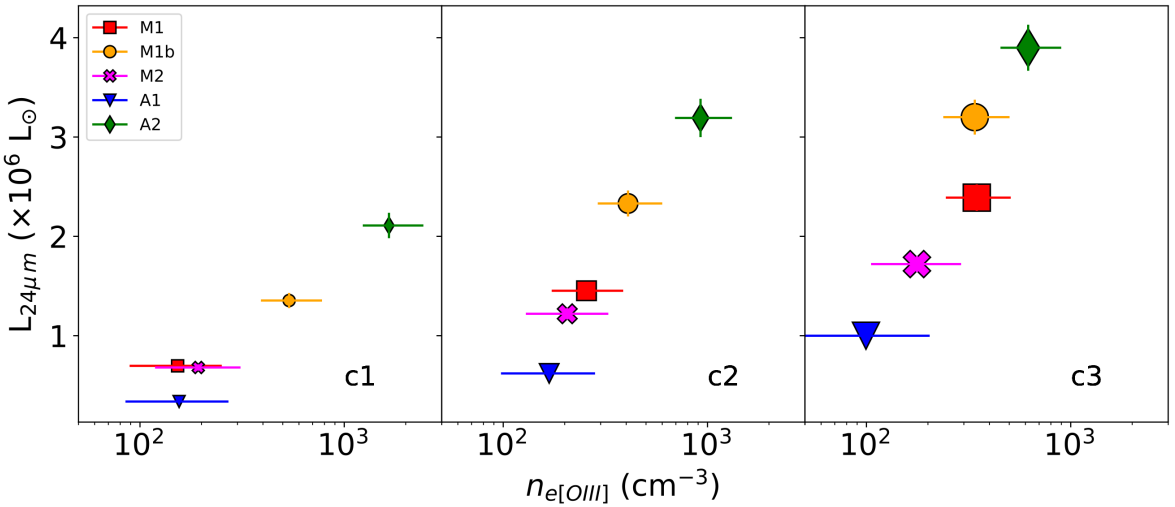
- Higher $n_{e[OIII]}$ found in more energetic environments

Effect of feedback on large scales:
Electron density in the ionised gas

IC10

Correlation with 24µm: embedded HII regions

Polles et al. subm.



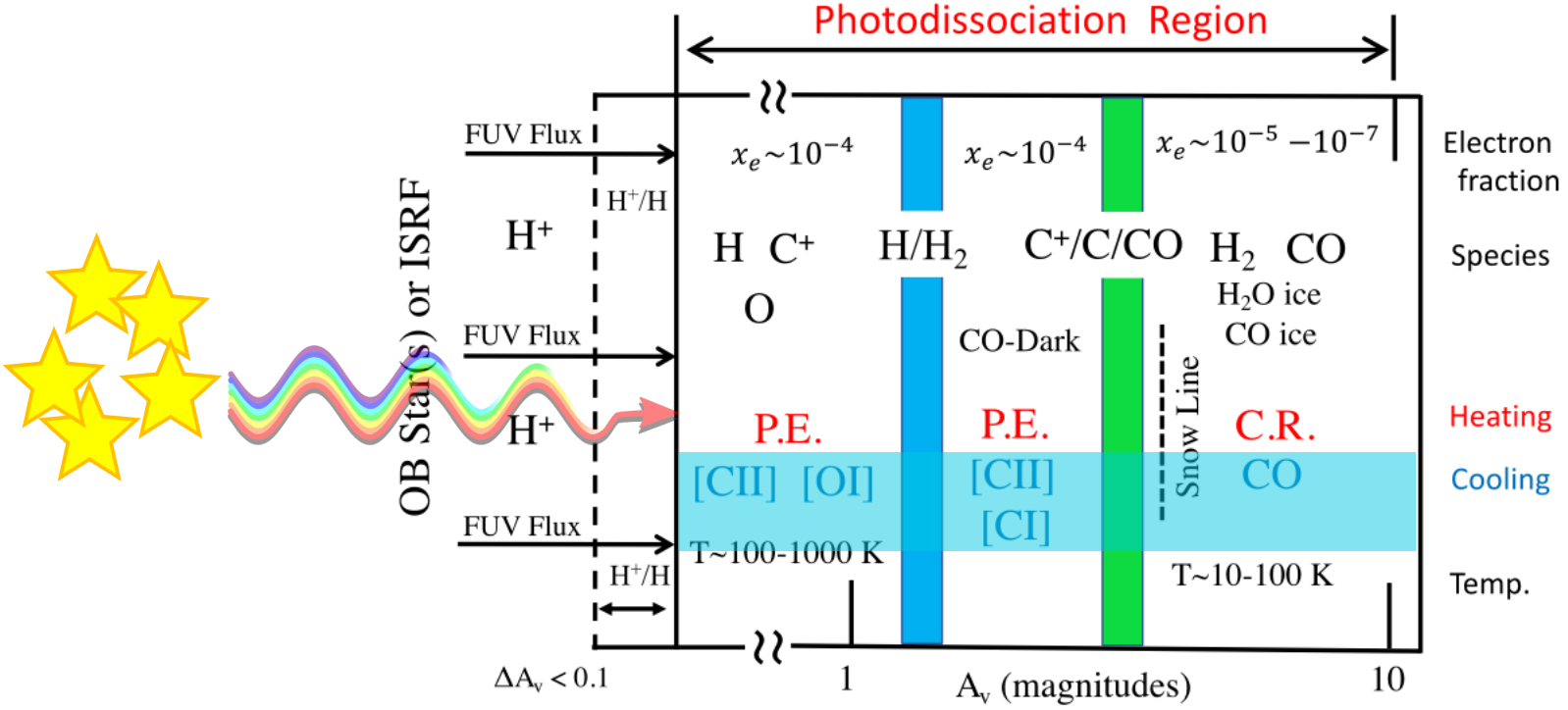
- Higher $n_{e[OIII]}$ found in more energetic environments
- Densest HII regions (in $n_{e[OIII]}$) are also the dustiest

—> $n_{e[OIII]}$ indicator of the **evolutionary stage** of the HII region and of the **hardness** of the radiation field

Effect of feedback on small scales:

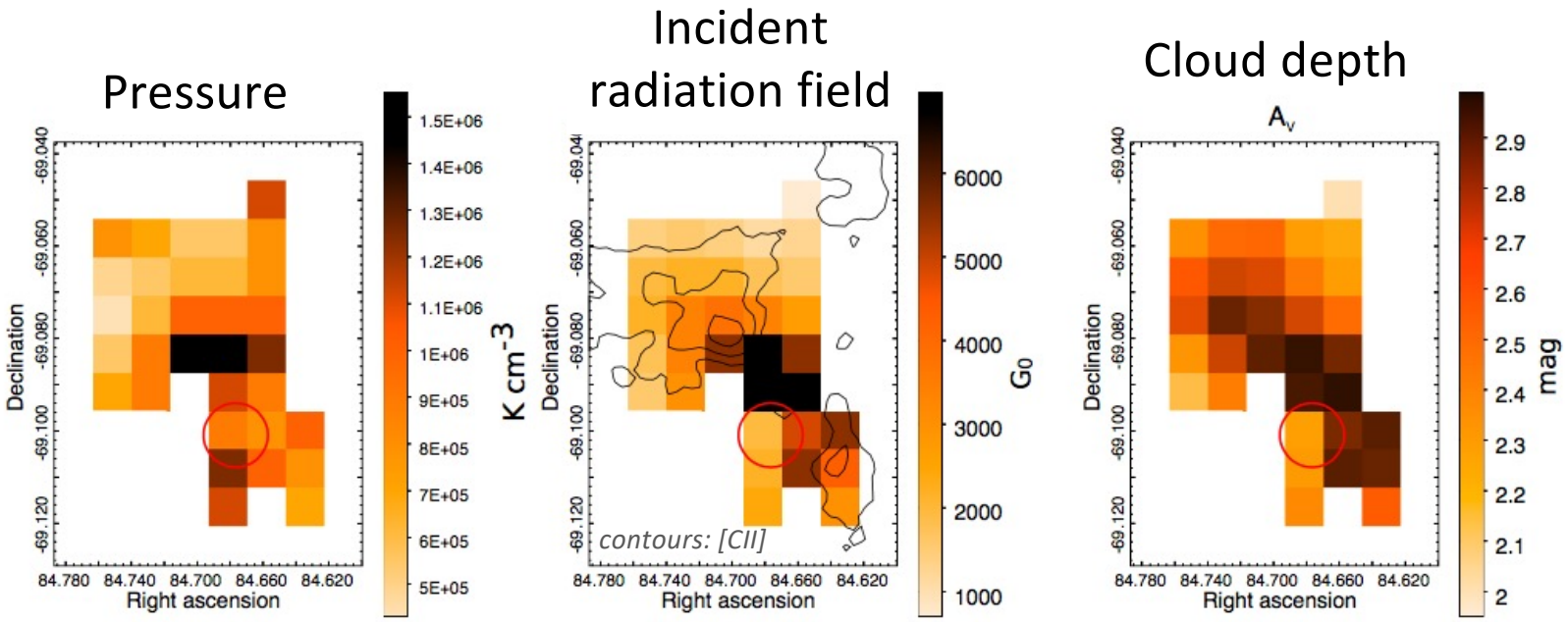
Structure and physical conditions of the neutral gas

Wolfire, Vallini & Chevance (ARAA, 2022)



Effect of feedback on small scales:
Structure and physical conditions of the neutral gas

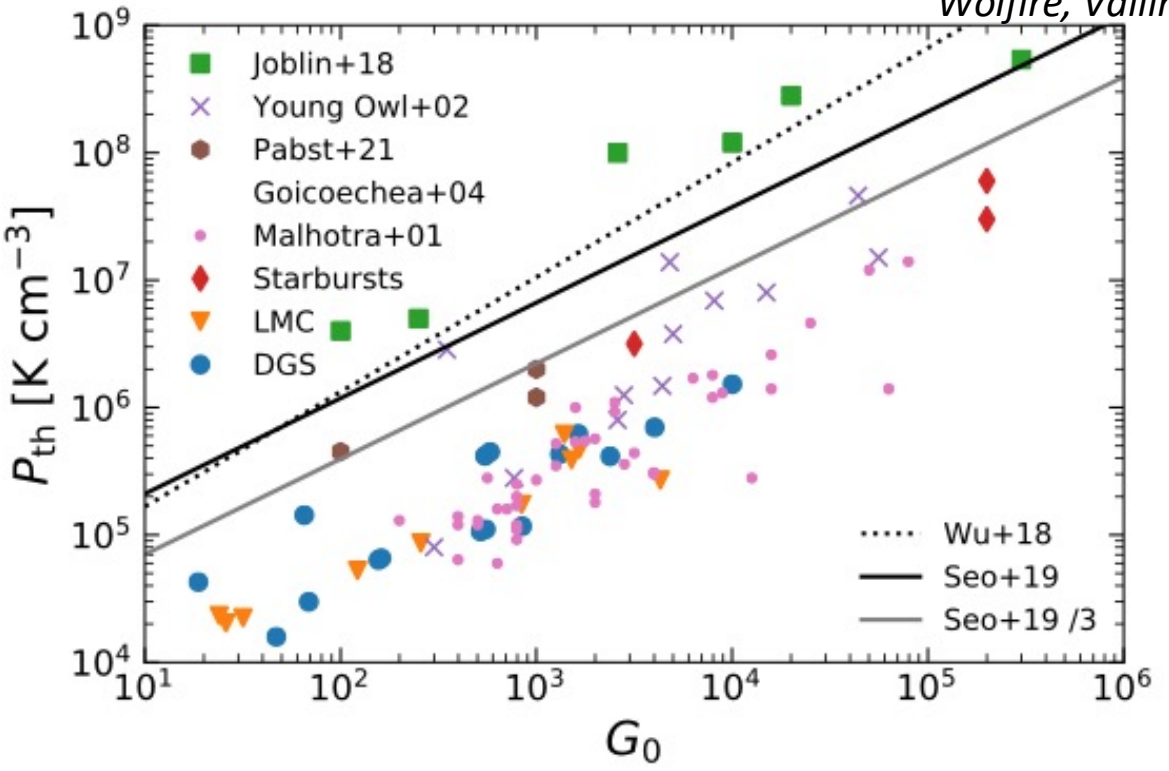
PDR model constrained by *[CII]*, *[OI]*, L_{FIR} and *[CI]* in 30 Dor



Chevance et al. 2016
Chevance et al. 2020b

Effect of feedback on small scales:
Structure and physical conditions of the neutral gas

Wolfire, Vallini & Chevance (ARAA, 2022)

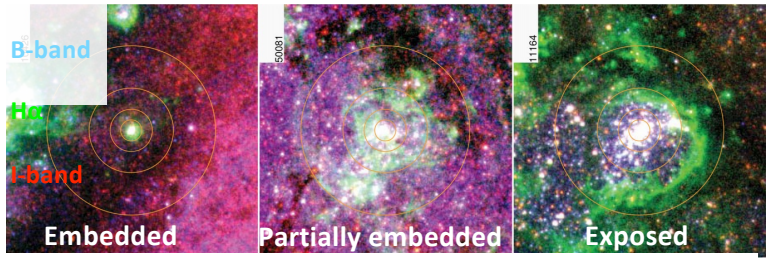


→ Also see Javier Goicoechea's talk

Effect of feedback on small scales:
Efficient and fast cloud destruction

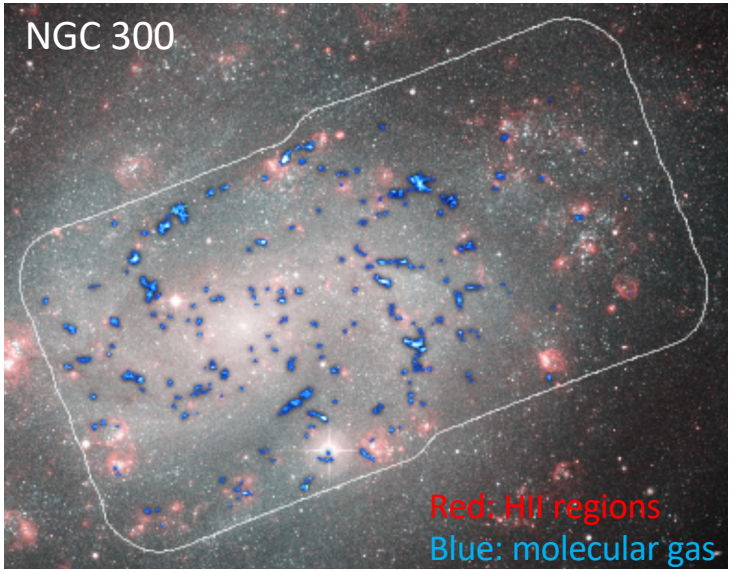
Young clusters are found to be **gas-free** after ~ 4 Myr

Hollyhead et al. 2015



See also Whitmore et al. 2014, Grasha et al. 2018, 2019, Hannon et al. 2019, Messa et al. 2021

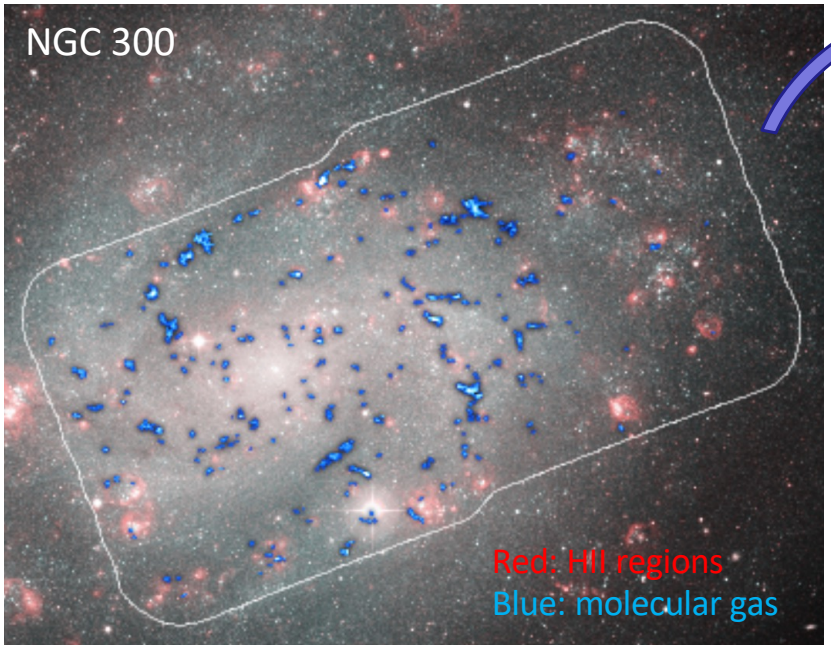
On galaxy scales, small-scale decorrelation between gas and young stars indicates a **rapid feedback phase**

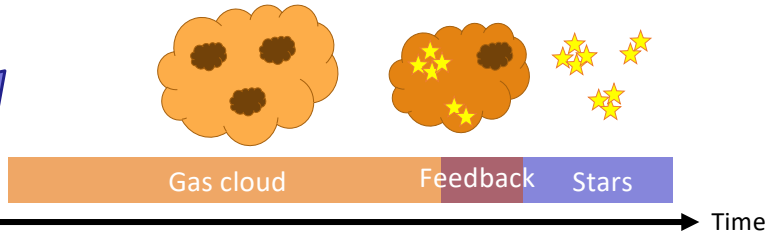


Kruijssen et al. 2019

Effect of feedback on small scales:
Efficient and fast cloud destruction

Small-scale variations of gas-to-SFR ratio reflect underlying timeline *(Kruijssen & Longmore 2014, Kruijssen et al. 2018)*





Small scale ***spatial decorrelation***

↓

Short temporal overlap between gas and stars

↓

Rapid feedback

(durations measured quantitatively through analytic fit of the gas-to-SFR ratio)

Rapid cloud dispersal

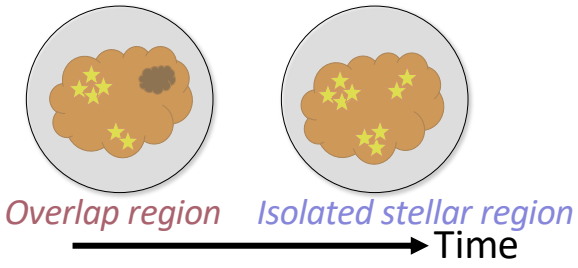
Or is the cloud just a bit further away?

Kruijssen, Chevance, Longmore et al. (subm.)

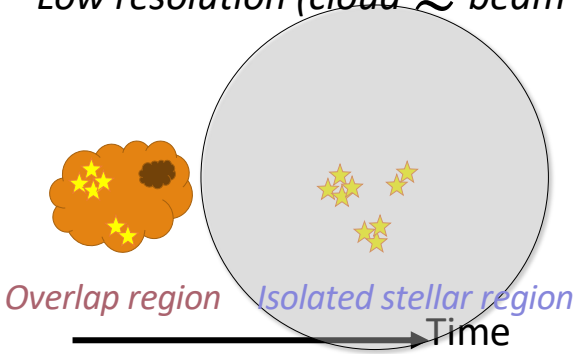
On arXiv yesterday!

Cloud dispersal

High resolution (beam $\lesssim$ cloud)



Low resolution (cloud $\lesssim$ beam $\lesssim \lambda$)



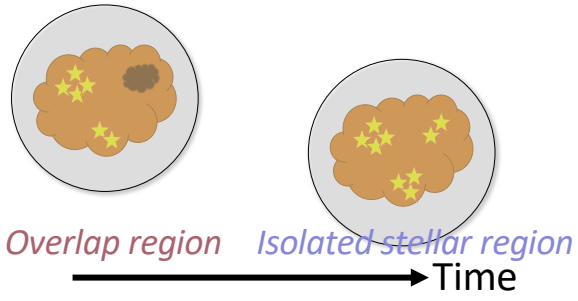
Duration of feedback phase ***constant*** with increasing beam size

Duration of feedback phase ***increases*** with increasing beam size

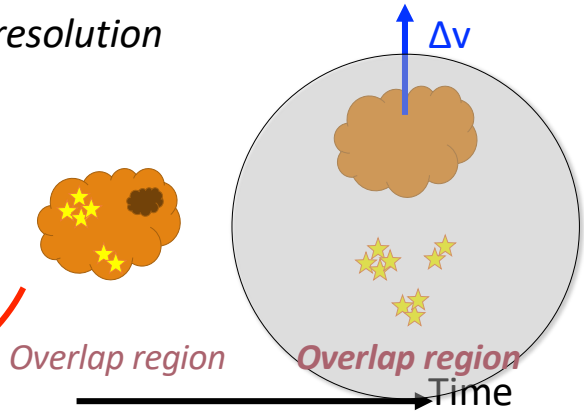
Drift

Koda & Tan (2023)

High resolution



Low resolution



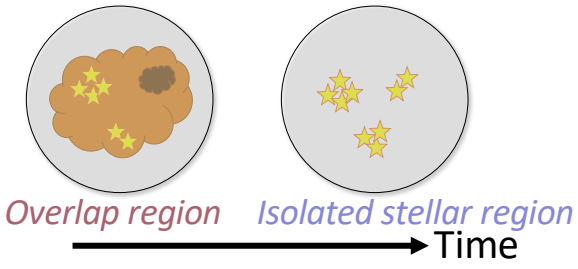
Rapid cloud dispersal

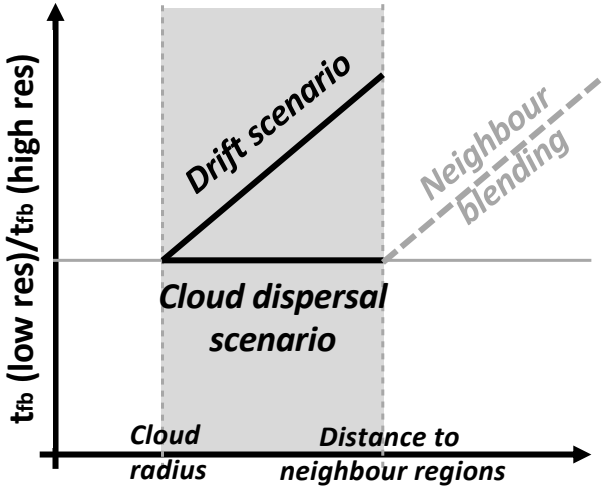
Kruijssen, Chevance, Longmore et al. (subm.)

Or is the cloud just a bit further away?

Cloud dispersal

High resolution (beam ≲ cloud)

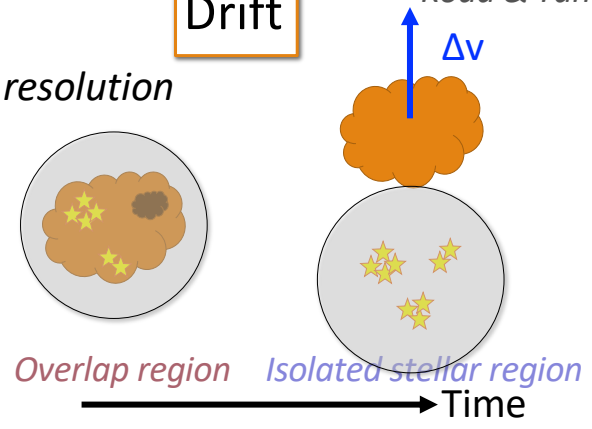




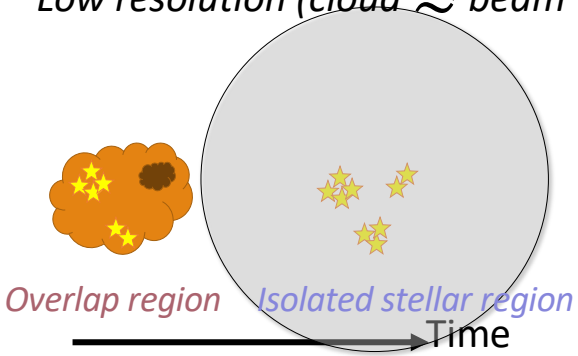
Drift

Koda & Tan (2023)

High resolution



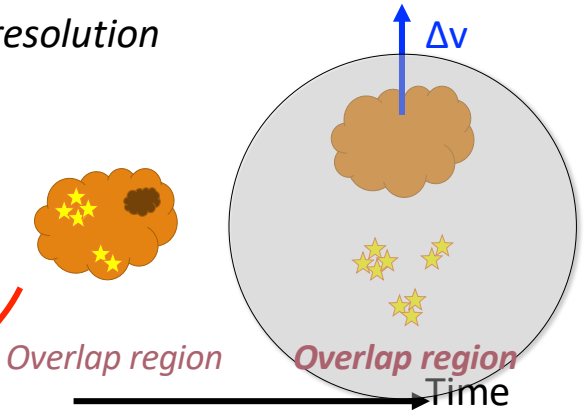
Low resolution (cloud ≲ beam ≲ λ)



Duration of feedback phase ***constant*** with increasing beam size

Duration of feedback phase ***increases*** with increasing beam size

Low resolution



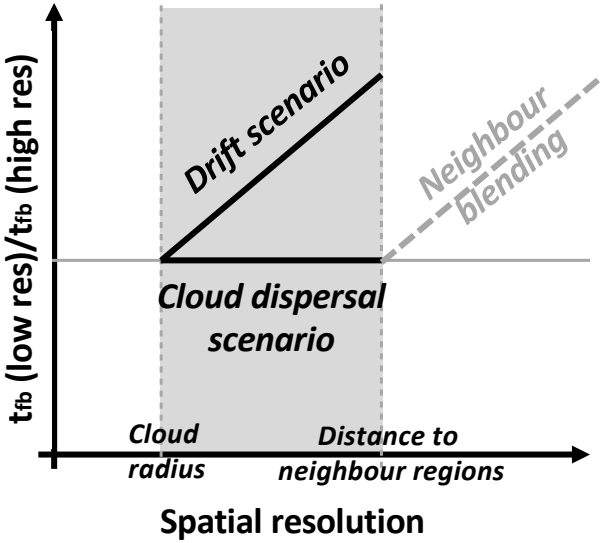
Rapid cloud dispersal

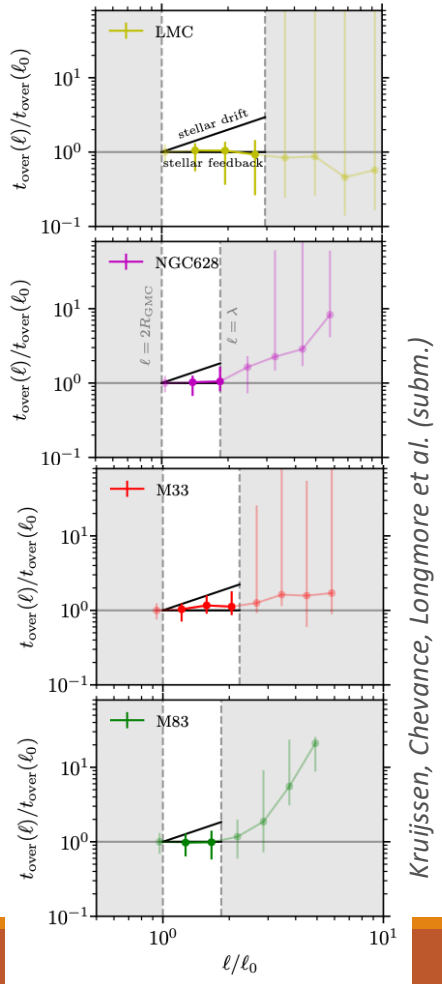
Or is the cloud just a bit further away?

Kruijssen, Chevance, Longmore et al. (subm.)

Cloud dispersal

Duration of feedback phase ***constant*** with increasing beam size





Drift

Koda & Tan (2023)

Duration of feedback phase ***increases*** with increasing beam size

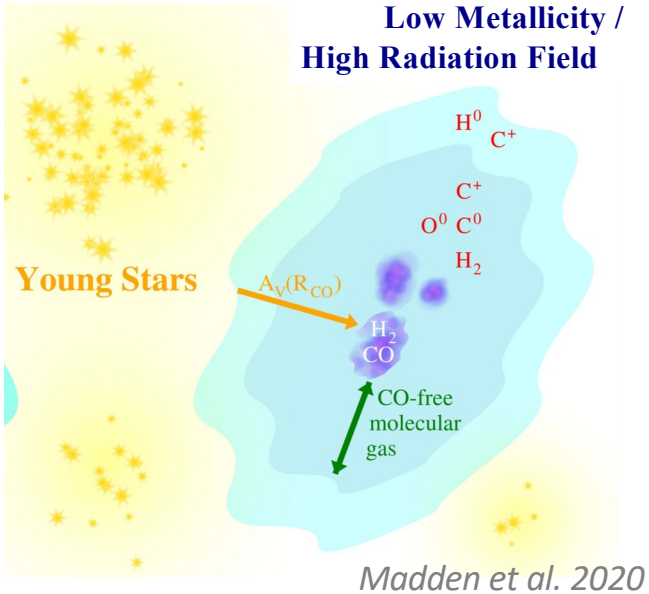
Dispersal scenario highly favoured over drift scenario (globally and for individual galaxies)

Understanding the multi-phase structure and physical conditions of the ISM in nearby galaxies

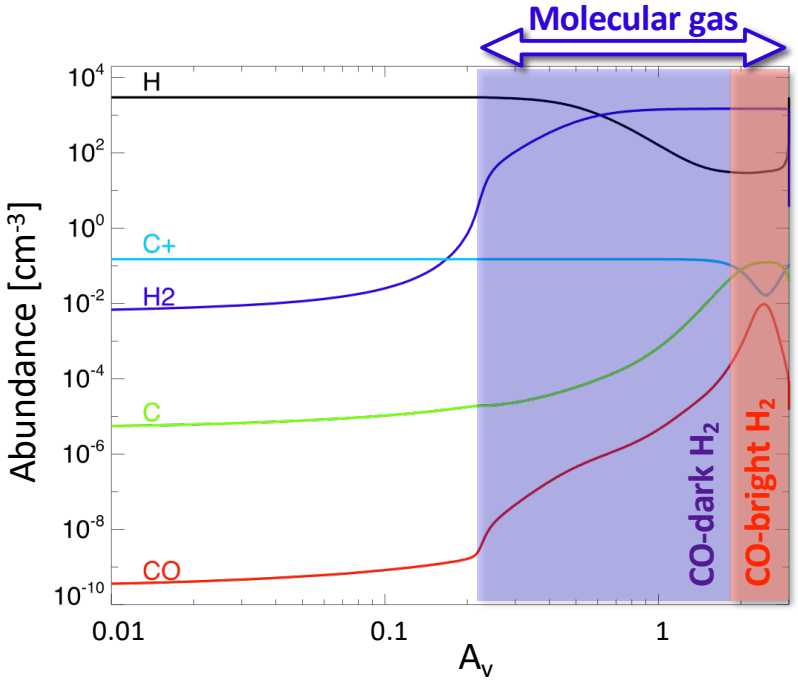
- What are the effects of feedback on the surrounding medium?
  - What are the characteristics of the radiation field?
  - What are the physical conditions of the multi-phase ISM?
  - Are the molecular clouds destroyed by feedback?
- What is the (total) reservoir of star-forming gas?

Mélanie Chevance

What is the total reservoir of molecular gas?



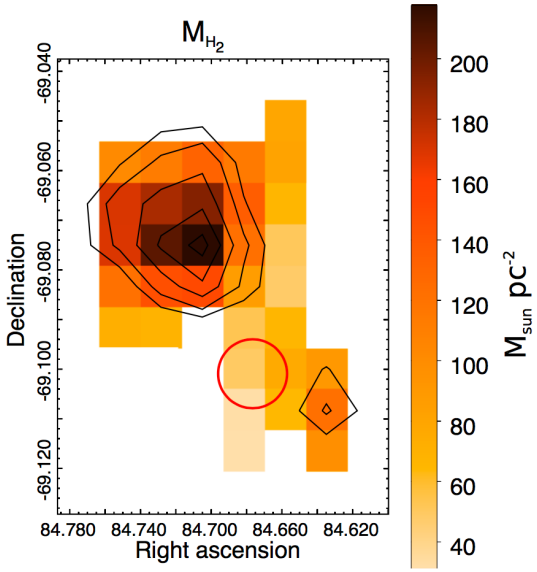
Madden et al. 2020

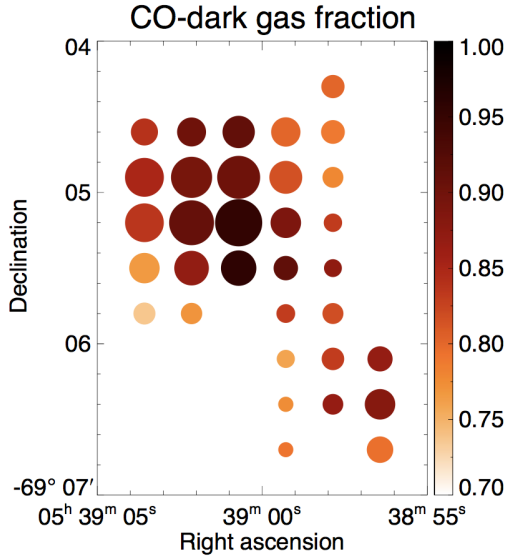


What is the total reservoir of molecular gas?

Total H_2 mass
predicted by PDR model
([CII], [OI], L_{FIR} and [CI] in 30 Dor)

$$N(H_2) = X_{CO} \times I_{CO}$$





More than 75%
of the molecular gas
not traced by CO

→ See Suzanne Madden's talk

Chevance et al. 2020b

Understanding the multi-phase structure and physical conditions of the ISM in nearby galaxies

- In massive star-forming regions, the vast majority of the molecular gas is **CO-dark**

- This is driven by:
  - the **intense radiation field** from the central cluster
  - the **high porosity** of the gas in moderate to low-metallicity environments, allowing a large fraction of the photons to escape young stellar regions

- Efficient pre-SN feedback **disperse** the GMCs within ~1-5 Myr

Mélanie Chevance